STUDY OF IONIZING SHOCK WAVES GENERATED BY A THETA-PINCH IN AN ARGON GAS

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THESIS

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GENERATED BY A THETA-PINCH
IN AN ARGON GAS

by

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June 1972

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ABSTRACT

A study was made of shock waves produced in neutral argon gas by a theta-pinch device. From the study, graphs were made of the velocity of the shock wave observed versus the applied magnetic field, the bank voltage of the capacitor bank, and the argon pressure in the plasma chamber. The velocity of the shock front varied with the parameters as follows:

Parameter Varied	Range	Velocity
Pressure	20 microns	4.01×10^5 cm/sec
	1000 microns	2.20×10^5 cm/sec
Applied Magnetic Field (for 15KV)	0 Gauss	4.00×10^5 cm/sec
	6000 Gauss	2.10×10^5 cm/sec
Applied Magnetic Field (for 10KV)	1800 Gauss	2.6×10^5 cm/sec
	3600 Gauss	2.3×10^5 cm/sec
Bank Voltage	15 KV	3.25×10^5 cm/sec
	10 KV	2.50×10^5 cm/sec

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ACKNOWLEDGEMENT

During the project many people gave aid and assistance to assure its success. These people were Professor A. W. Cooper, who provided the guidance for the project; Mr. Hal Herreman, who was always on hand to explain a problem or find the right wrench; Mr. Mike O'Day, who was always there when a new spark gap was needed or a part manufactured. To them, I extend my appreciation for their help.

I. INTRODUCTION

This research report is a continuance of a project started at the Naval Postgraduate School to study the generation and propagation of collisionless shock waves in a plasma. The project started with the construction of the theta-pinch by Dennis M. Budzik and was continued by Charles C. Christensen in his thesis, Investigation of Theta-Pinch Produced Shock Waves in a Plasma [13].

This project is stimulated by the interest in the collisionless shock wave phenomena observed in the interaction of the earth's magnetosphere and the solar wind and the applications of this mechanism to controlled thermonuclear fusion. The collisionless shock wave arises from the fact that the particle interaction distance or mean free path between collisions is on the order of the size of the solar system and yet shock waves are observed.

With this in mind an investigation of the shock waves produced by the theta-pinch in rarefied neutral argon has been conducted in this experiment. The velocity of the shock wave was investigated as various parameters were varied holding others constant. First the Applied Magnetic field was varied and plots of the velocity of the shock versus magnetic field were obtained, secondly the theta-pinch bank voltage was varied holding the pressure and applied magnetic field constant and then the pressure was varied holding the Magnetic Field and Bank Voltage constant. These observations

were made with photomultipliers, and magnetic and electrostatic probes. The limits of the operation of the theta-pinch were such that observations of collisionless waves were not possible. The observation and experimentation was conducted in the region of collisional ionizing shock waves.

II. THEORY

A. THETA PINCH

The theta-pinch mechanism involves the passage of a high current through a coil in a short time element. This current azimuthally directed around the coil creates an induced magnetic field $\vec{B}_z$ (See Figure 1). The induced azimuthal electric field due to the time derivative of magnetic flux density produces breakdown of the gas at the maximum radius in the pinch tube. A current is set up in this ionized layer that opposes the current in the coil, creating a current density $\vec{J}_\theta$ azimuthally around the coil. This current now creates a $\vec{J}_\theta \times \vec{B}_0$ force which is directed radially inward and the ionized layer of gas, being a conductor, excludes magnetic fields. The induced magnetic field proceeds radially inward sweeping up the charged particles in its path and these particles colliding with neutral particles give increased ionization and a collapse of the pinch. The gas is compressed to high temperatures and densities in the middle of the pinch tube. The plasma being highly ionized is assumed to be infinitely conducting and this excludes the outside compressing B_z and traps the initially applied field inside the plasma. When the initial field is trapped it is carried inward with the plasma and the lines are also compressed raising the value of the internal field. This internal field exerts a magnetic pressure and when this pressure reaches a value where it is equal to the outside compressing force the pinch collapse halts.

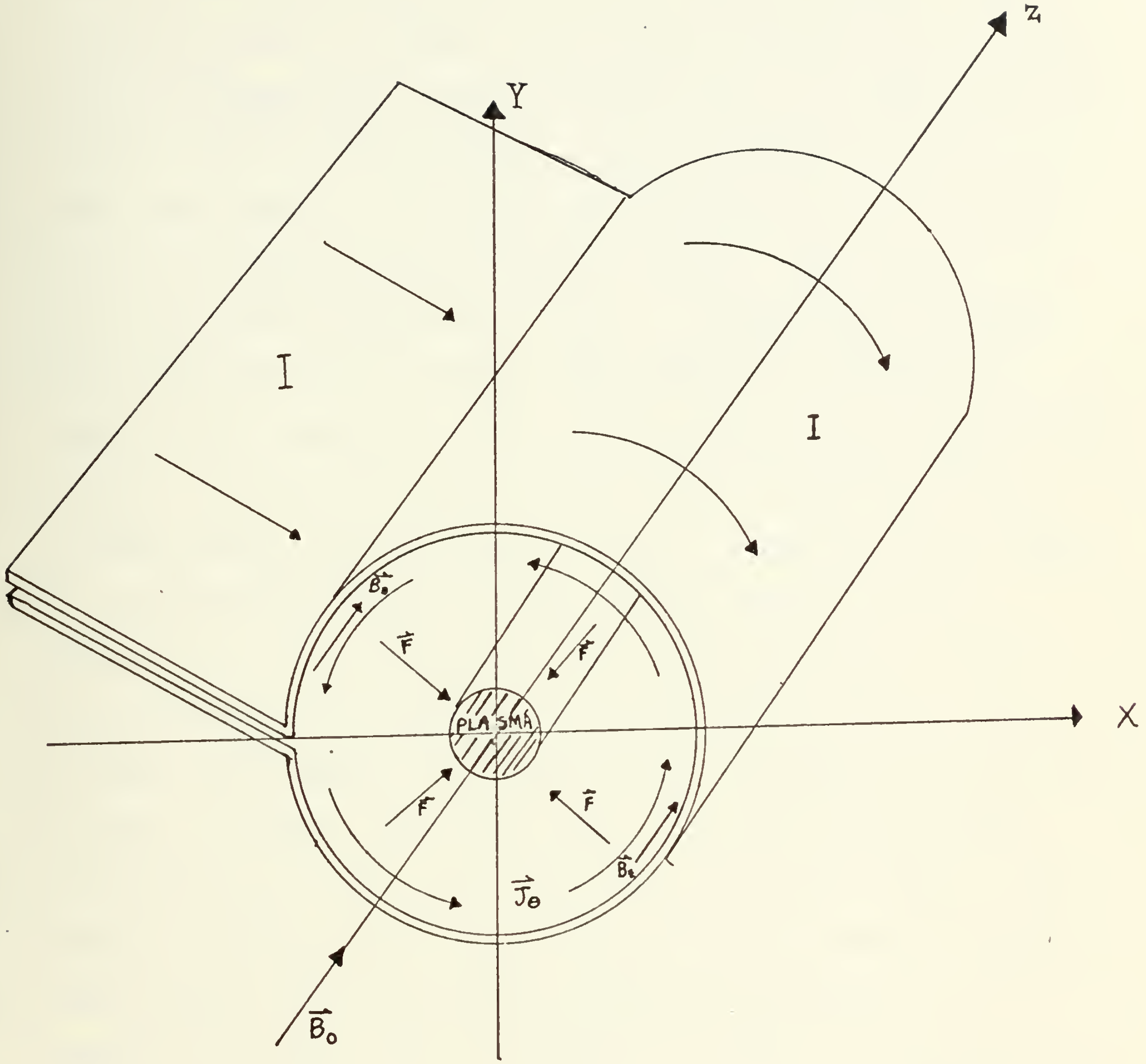

Figure 1. Schematic of theta pinch in operation.
I - applied current; $\vec{B}_z$ - induced magnetic field
$\vec{J}_\theta$ - induced current; $\vec{F}$ - radial $\vec{J}\times\vec{B}_0$ force.

K. V. Roberts [1] in his article on theta-pinch ionization made a numerical analysis of a theta-pinch operation. The radial profiles in figures two through five show values numerically obtained for a specific theta-pinch. In these profiles Roberts labels three positions. The Z position is the plasma edge, the radius of the pinch was 4.6 cm. The Y position is the point of zero induced magnetic field. The X position is the shock front propagating inward. Between these boundary lines are four areas Roberts labels Regions I through IV. Region I is a region of very low density partially ionized gas outside the main discharge. Region II is a region of fully ionized plasma between points Y and Z. Region III is a region of hot partially ionized plasma between points X and Y. Region IV is a central core of cold un-ionized gas. These regions propagate inward until the pinch is complete. Figure 2 shows the propagation of these regions inward as a function of time. Figure 3 shows the radial profiles of the plasma parameters at a time of 0.64 microseconds after firing of the pinch. It can be seen in the figure that the induced magnetic field forms a front outside the ionized plasma which is pushing the plasma inward causing an increase in density in the plasma in front of the magnetic field and an increase in neutral density ahead of that. Figure 4 shows the velocity profile of the gas collapsing in the pinch. Notice the plasma is fully ionized between points Y and Z and the plasma has its maximum velocity in this area. Figure 5 shows the ion and electron temperatures at the same time as the previous profiles.

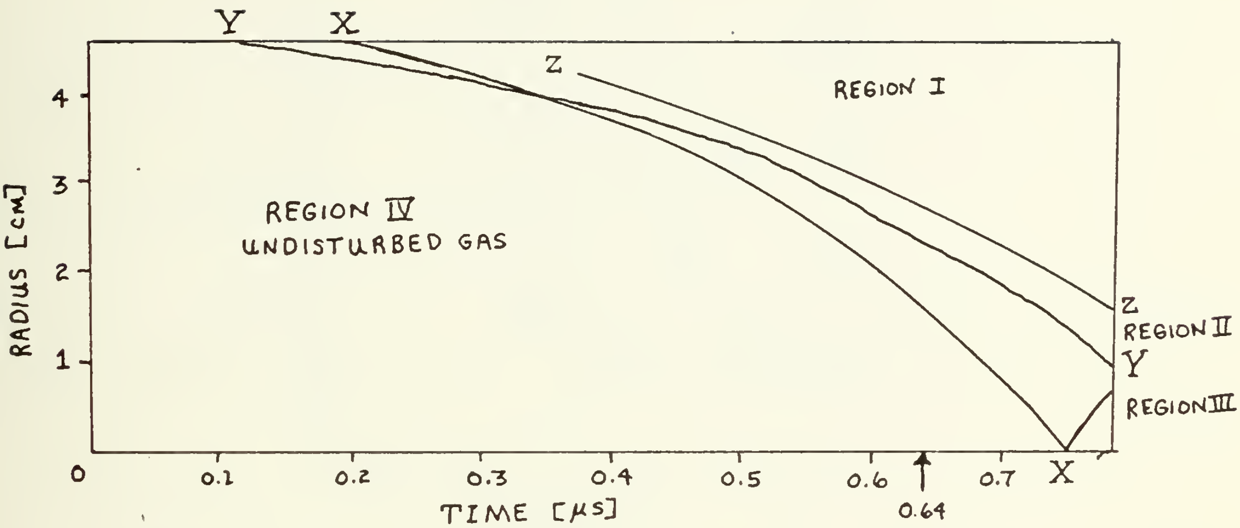

Fig. 2. Shows propation of regions I-IV inward with time. (K. V. Roberts [1])

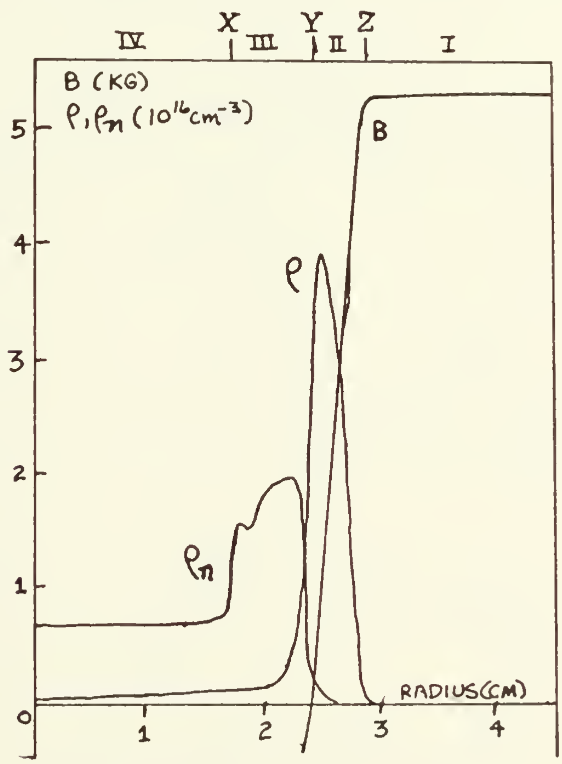

Fig. 3. Profiles of plasma density ρ, neutral density ρ_n and magnetic field at T=0.64 microseconds. (K. V. Roberts [1])

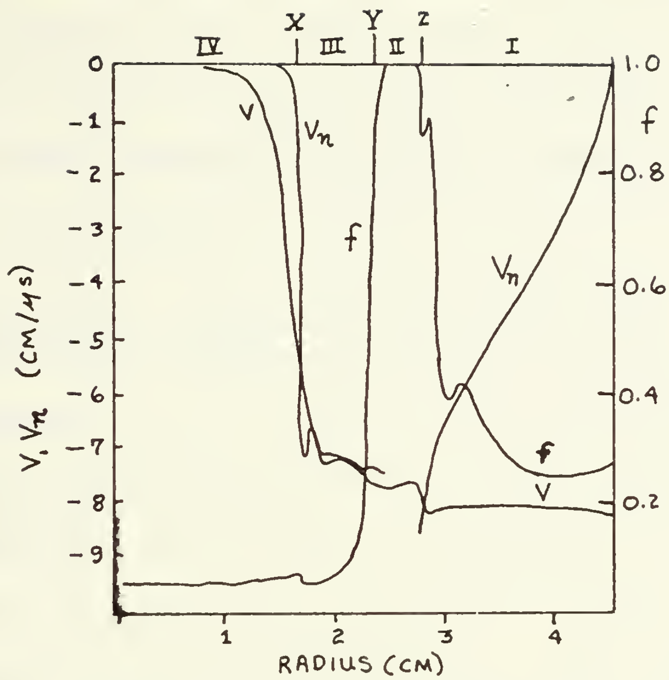

Fig. 4. Plasma velocity V, neutral V_n and fractional ionization f at t=0.64 microseconds. (K. V. Roberts [1])

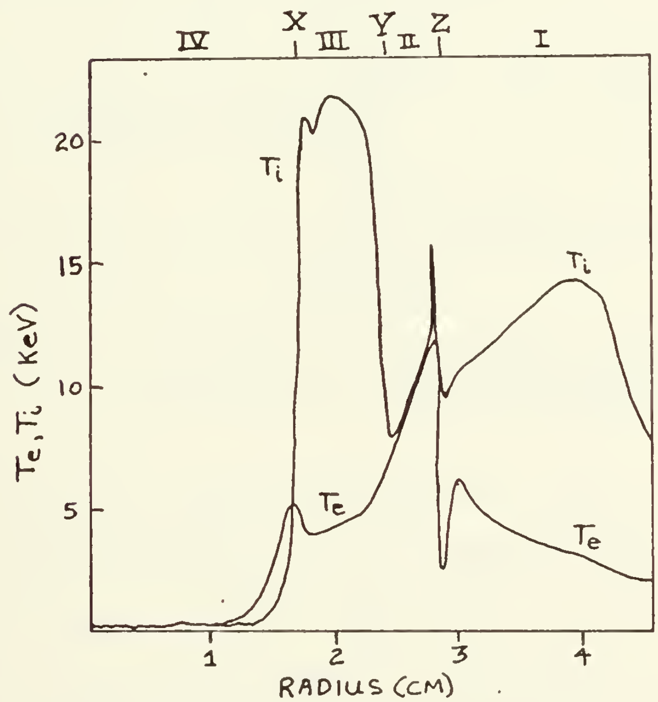

Fig. 5. Ion temperature T_i and electron temperature T_e at t=0.64 microseconds. (from K. V. Roberts [1])

These profiles progress inward until the pinch effect is halted. There is now a highly dense and hot plasma which is fully ionized along the center of the pinch. This creates a very steep temperature and pressure gradient at the ends of the theta-pinch coil.

B. FORMATION AND PROPAGATION OF SHOCK WAVES IN THE PLASMA COLUMN

The pressure gradient and temperature gradient mentioned in the previous section tend to propagate down the plasma column causing a shock front to propagate if the density gradient is of sufficient steepness to give a shock velocity. The gradients appear as in Figure 6. The temperature gradient is not as steep due to radiation heating which preheats the gas before arrival of the shock wave.

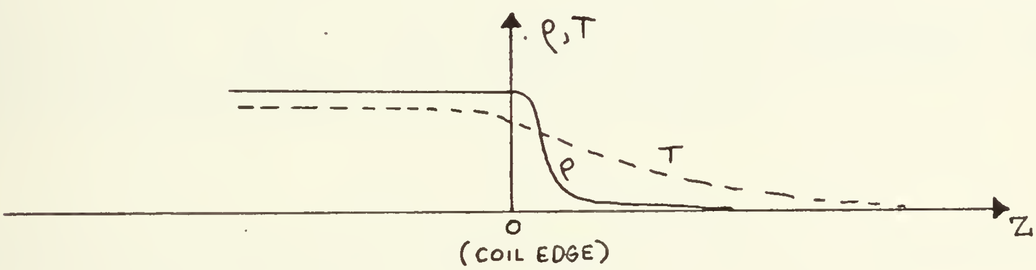

Fig. 6. Pressure and temperature gradients from end of the theta-pinch coil.

This density gradient produces a shock wave traveling down the column parallel to the applied magnetic field and this is known as a normal shock wave. The shock wave will propagate as long as the density gradient is maintained. In the theta-pinch the density gradient is very short in duration and the shock as it propagates down the tube will diminish in

strength and velocity due to diffusion of energy from the front to the column walls and energy expended across the front. There is no constant source of energy in this system after the wave leaves the pinch to sustain the front. The distance of propagation of the shock front down the plasma column will depend on the applied energy from the theta pinch coil and the rate of loss of energy from the front as it propagates.

C. IONIZING SHOCK FRONTS

Gross [2] defines an ionizing shock front as follows

> An ionizing shock is defined as a compressive wave which propagates into an unionized, non-conducting gas, ionizes it, and mkes the post shocked gas electrically conducting and capable of interacting with an electromagnetic field

Various other papers written on the subject state the same definition. Most of these papers use as a parameter the Alfvenic Mach Number which is defined as

$$M_A = U_1 / V_A$$

where U_1 is the shock front velocity and V_A is the Alfvenic velocity in the preshock gas defined as follows

$$V_A = \frac{B_z}{\sqrt{\mu_o \rho_o}}$$

B_z is the applied magnetic field and ρ_o is the density of the preshocked gas.

Levine [3] divided the shocks into three categories, the sub-alfvenic shock waves ($U_1 < V_A$), the trans-alfvenic shock

waves ($V_A < U_1 \leq 3V_A$), and the super-alfvenic shock waves ($3V_A < U_1$). The properties and behavior of the shock waves in these three regions have been investigated.

In the sub-alfvenic region the shock front velocity is less than the Alfvenic velocity but greater than the sound velocity a_1 where

$$a_1 = \sqrt{\frac{\gamma P_1}{\rho_1}}$$

In this region the shock wave can be described by the ordinary hydrodynamical shock wave theory. An investigation in this area by Miller [4] has been conducted and he reported that switch-on behavior has been measured in this area. Switch-on behavior is the appearance of a transverse component of the magnetic field appearing behind the shock front. In Figure 7, this region is the region below $U_1 = 1$. The solutions to the jump equations proposed by Taussig [5] in this area lay between the null shock and gas dynamic shock solution.

The second region is the trans-alfvenic shock wave region and has been investigated by various research groups. The shock wave velocity is greater than the alfvenic velocity and less than three times the alfvenic velocity. Normal shock waves propagating at these speeds are expected to exhibit "Switch-on" characteristics. Levine [3] states

> At trans-Alfvenic shock speeds, the solutions (to the one dimensional shock tube problem) are switch-on shock waves.

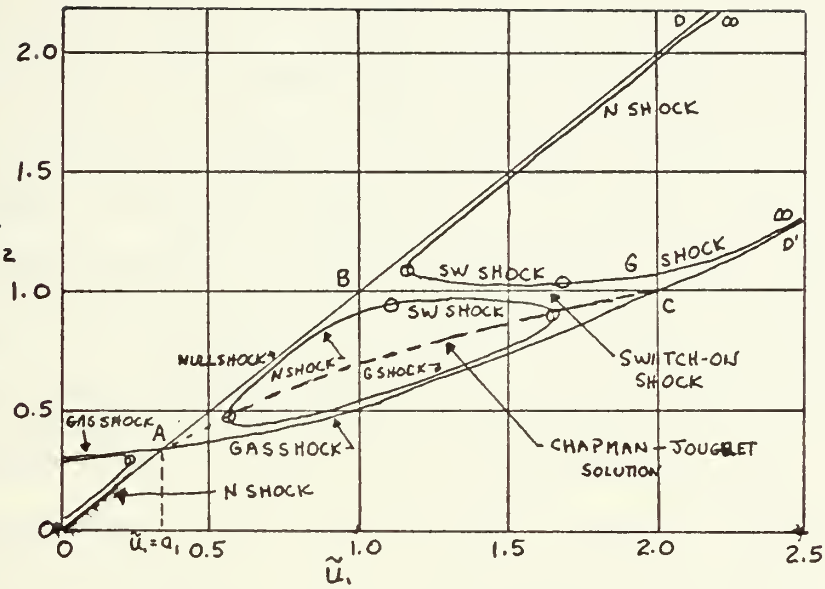

Fig. 7. Ionizing Shock Wave Solutions.
Non-dimensional flow velocity $\tilde{U}_2$ vs non-dimensional mach number. (From Taussig [5])

These are characterized by an electrical field precursor in the preshock gas transverse to the shock front which combines with the current flow in the shock front to produce the switching on of a transverse component of the magnetic field in the post-shocked gas.

Levine is referring to the solutions by Taussig [5,6]. In his solutions Taussig treated the shock as a one dimensional discontinuity separating a region of zero conductivity (un-ionized gas) from a region of infinite conductivity (a fully ionized plasma) [5]. His assumptions were considered valid as most research work involves cylindrical geometry and in experiments involving conditions with the geometry of the

shock tube including the observed values had no appreciable deviations from one dimensional behavior [3]. Taussig also found that the usual shock jump equations (MHD-Rankine equations) were inadequate to describe the state of the post-shock plasma uniquely. This occurs because the un-ionized preshock plasma can support an electrical field transverse to the direction of shock propagation. The value of this field is not specified by ordinary jump equations. Taussig then treated this electrical field as a controlled variable parameter and was then able to find solutions to the shock tube problem. His solutions are shown in Figure 7, Taussig solved the equations for the transverse electrical field equal to zero (the limiting cases) and for values of the field greater than zero. He found that the $E = 0$ case was the limiting case to the equation and the $E > 0$ cases were bounded by these solutions, forming closed contours. The $E > 0$ solutions were found to be contours inside the limiting values. The contours become smaller for higher values of E and therefore reach a maximum value above which no solutions exist. Taussig [5] calculated the maximum value to be

$$E_{max} = 0.357 \, [B_x^2 / (\mu\rho_1)^{\frac{1}{2}}]$$

(Gross [2])

This has been verified experimentally by Cross [7] and Gross, et al. [8]. (See Figures 8 and 9)

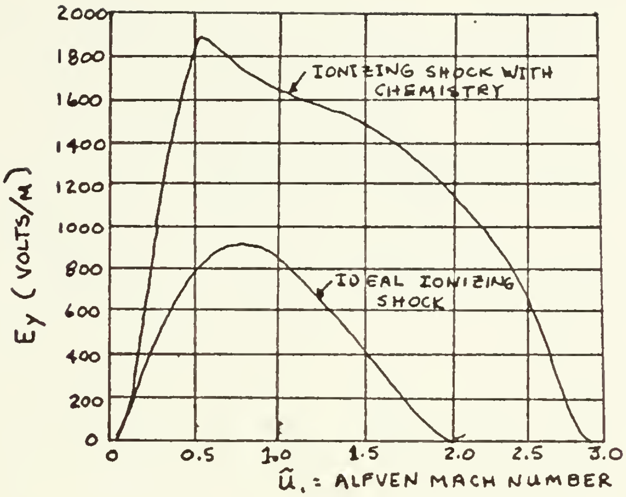

Fig. 8. Transverse electric field versus Alfven Mach number. Note the influence of chemistry on the magnitude of the electric field and the extent of the extremal ionizing shock regime. (R. A. Gross, et al. [8])

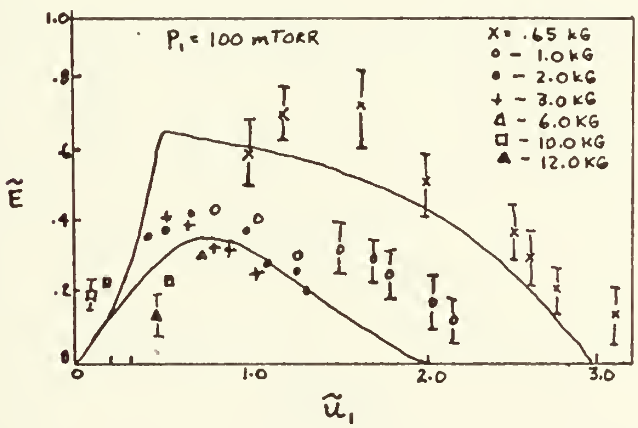

Fig. 9. Transverse electric field $\tilde{E}$ versus Alfven Mach number u_1 for various values of the axial magnetic field B_0. The units of E and u_1 are dimensionless. (R. C. Cross [7])

As can be seen in these figures the values of the transverse component to the electrical field increases to a maximum value and then decreases to zero at approximately $M_A = 3$. The value of the cutoff computed by Gross [2] with chemistry added is $M_A = 2.93$. This transverse component of the electrical field interacts with the current in the shock front (in shock tube problems) to switch on a transverse magnetic field component behind the shock front. This magnetic field varies with shock speed as does the electric field that produces it. The magnetic field peaks later than the electric field, but the peaks are relatively in the same range. (See Figures 10 and 11)

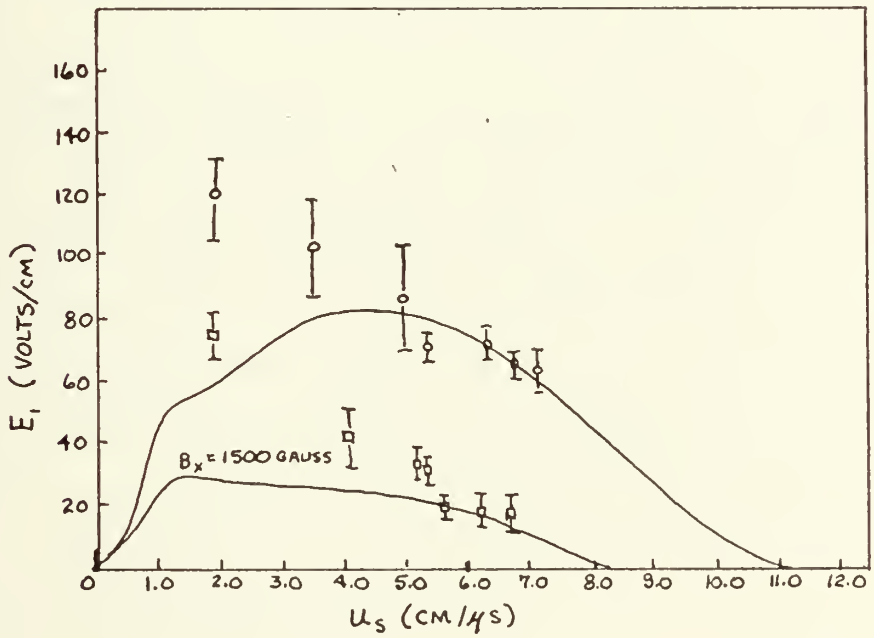

Fig. 10. Measured upstream electric field compared with theory. P_1 = 200mTorr;
□ = experimental data (B_x = 1500 gauss);
○ = experimental data (B_x = 2500 gauss);
(———) Chapman-Jouquet solution ionizing shock theory. (Levine [3])

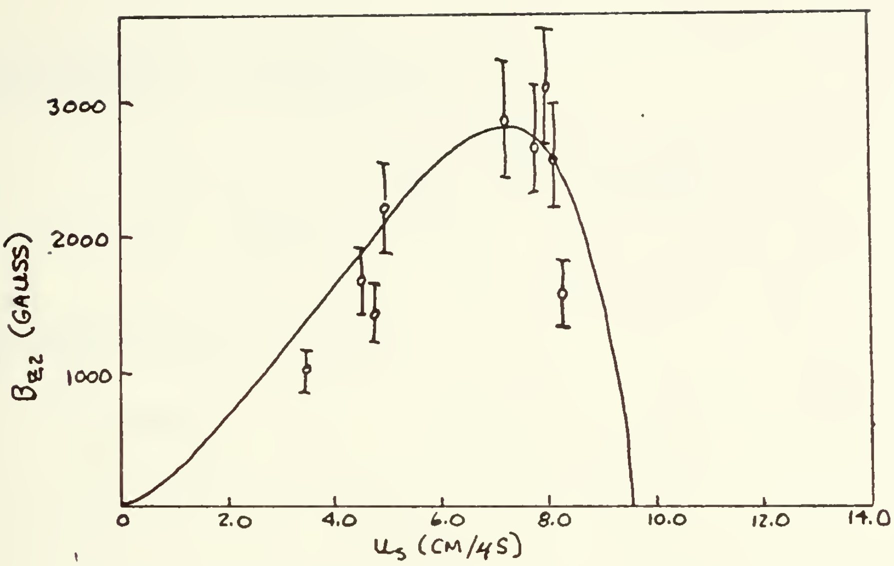

Fig. 11. Measures switch-on magnetic field compared with theory. P_1 = 200mTorr; B_x = 2000 gauss; O = experimental data; (———) Chapman-Jouguet solution, ionizing shock theory. (Levine [3])

The third region is the super-Alfvenic shock wave region ($U_1 > 3V_A$). At this point the preshock gas loses its ability to support the transverse electrical field and the wave equations revert to the normal MHD-Rankine jump equations and the solutions are uniquely determined. The shock waves are then described as ordinary gas dynamic shock waves having no shock front currents and no transverse electric fields. However switch on behavior has been detected in the super-Alfvenic region by Levine [3].

D. RANKINE-HUGONIOT JUMP EQUATIONS

The following equations are the equations for the jump conditions across the normal ionizing shock wave from Taussig [5].

Conservation of Mass

$$\rho_1 U_1 = \rho_2 U_2 = m \tag{1}$$

Conservation of Momentum

$$mU_1 + P_1 = mU_2 + P_2 + \tfrac{1}{2}(\mu H_y{}^2) \tag{2}$$

$$mw_2 - \mu H_z H_{y2} = 0 \tag{3}$$

Conservation of Energy

$$m(\tfrac{1}{2}U_1{}^2 + h_1) = m[\tfrac{1}{2}(U_2{}^2 + w_2{}^2) + h_2] + E_x H_{y2} \tag{4}$$

The subscripts 1,2 refer to the preshock and post-shock regions respectively. The U's are the velocities relative to the shock front, ρ is the density, E is the electric field, H is the magnetic field, and h is the specific enthalpy of the two states. The shock frame coordinate system is shown in Figure 12.

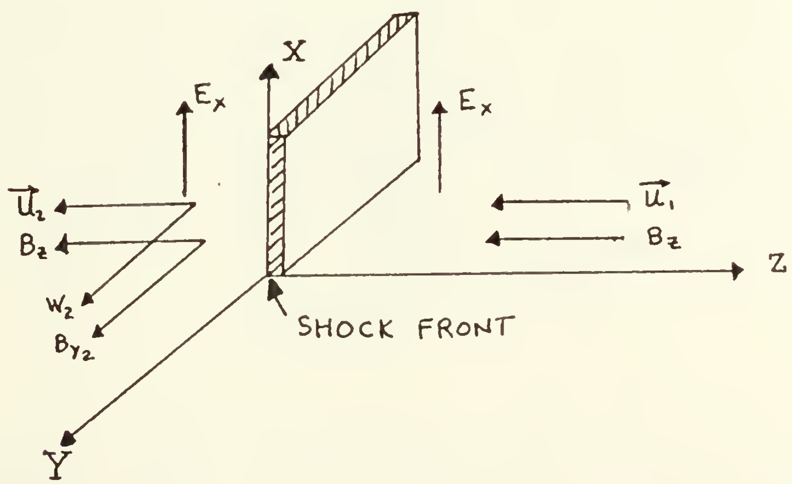

Fig. 12. Shock Frame Coordinate System

The equations were solved by Taussig, assuming $\gamma = 5/3$ and the results are shown in Figure 7.

E. STRUCTURE OF IONIZING SHOCK WAVES

A shock wave can be described as a thin layer through which the gas changes state. The thickness of the layer is of the order of several times the mean free path evaluated in the preshock gas (Perona and Axford [10]). We are studying the effect of ionizing shock fronts; therefore the gas is changing state from the undisturbed un-ionized gas to the highly ionized post-shock state. Perona and Axford [10] state that in a neutral gas the most important phenomenon that starts the ionization process, is usually ionization by atom-atom collisions. The atom-atom collision is a much less effective process than the electron-atom collision process. Therefore Perona and Axford [10] propose a shock structure as shown in Figure 13, where the region labeled thermal shock layer is the

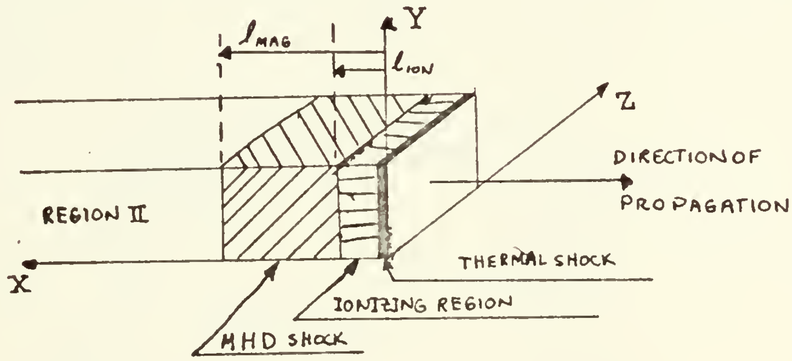

Fig. 13. Shock structure. (MHD shock-magnetohydrodynamic shock) (from Perona and Axford [10])

region of atom-atom collisional ionization and thermal heating by these collisions. After a certain amount of ionization

the electron-density is high enough that the electron-atom process takes over and the ionization rate increases rapidly, this is the ionizing region. Chubb [9] calls this first region the viscous shock region. The second region is where most of the ionization occurs. Ionization occurs until it is equal to the recombination rate behind the shock and equilibrium occurs. Chubb also states that for Mach numbers less than 20 little ionization occurs in the atom-atom region and this region becomes negligible. If the mach number is greater than 20 the atom-atom shock region is comparable to the ionization region and must be included into the calculations. Figures 14 and 15 show how the parameters of temperature, electron temperature, shock velocity, degree of ionization, and magnetic field change over the viscous shock and ionizing region for a pure hydrodynamic shock front (Figure 14) and a slow gas-ionizing front (Figure 15). These are plotted on a dimensionless basis.

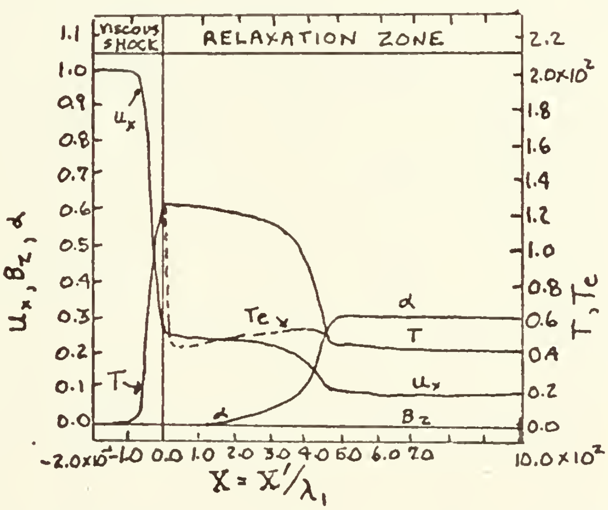

Fig. 14. Nonequilibrium structure of a pure hydrodynamic front with $E_x = B_x = B_z = 0$ in the Zeldovich-von Neumann-Doring approximation, evaluated for $M_1 = 20$. Note the scale change between X<0 and X>0. (From Chubb [9])

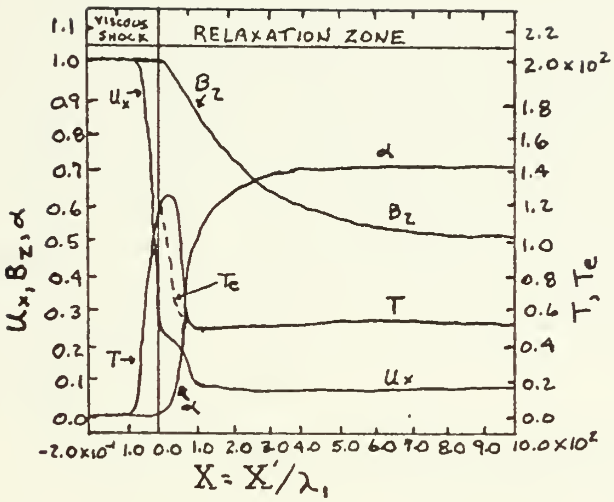

Fig. 15. Nonequilibrium structure of a slow gas ionizing hydromagnetic front with $M_A = 2$, $E_X = 1.0$. Note the scale change from $X<0$ and $X>0$. (From Chubb [9])

In Figure 15 it can be seen that the degree of ionization is low across the viscous shock and increases rapidly in the relaxation zone to an equilibrium value. Also the temperature increases across the boundary to an equilibrium value. These regions are followed by magnetohydrodynamic shock, whose width is usually larger than the ionization region. Perona and Axford [10] calculate the characteristic length in Argon of the viscous shock region ($l_{aa} = 2 \times 10^{-4}$ cm), the ionizing region ($l_{ion} = 13$ cm), and the magnetohydrodynamic region ($l_{mag} = 50$ cm). This gives an overall width of the shock front of approximately 63 cm. These widths were calculated for an Alfven velocity of 1750 m/sec (See Figure 13).

F. PLASMA LAB FACILITIES

1. Theta-Pinch

The theta-pinch consists of a capacitor bank of six 7 microfarad capacitors connected in parallel and charged by a 50 KV power supply. This stored energy is then discharged into six strip lines to the theta-pinch coil through six spark gap switches which are fired simultaneously by a master switch. (See Figures 16,17,18, and 19). The parameters of the theta-pinch from Budzik [12] are:

PARAMETERS OF THE THETA-PINCH

Charging Voltage	25KV
Capacitance	42 Microfarads
Stored Energy	13.1 KJoules
Peak Current	255 KAmps
Discharge Ringing Frequency	172 KHz
Peak Flux Density	20 KG
Initial Rise Time of Current	1 Microsecond
Coil Length	14.5 cm
Coil Diameter	5.5 cm
Inductance of Coil	18 nH
Total System Inductance	64 nH

A more detailed description of the theta-pinch will be found in Budzik [12].

2. Plasma Chamber

The plasma chamber consists of a 10 foot horizontal pyrex tube composed of a cathode end one foot in length with a nine foot drift section. The theta-pinch is located seven feet from the cathode of the plasma column. For this study a preexisting plasma beam was not used. The column is placed in the center of a system of solenoidal magnets composed of six toroidal coils which are placed around and coaxial with

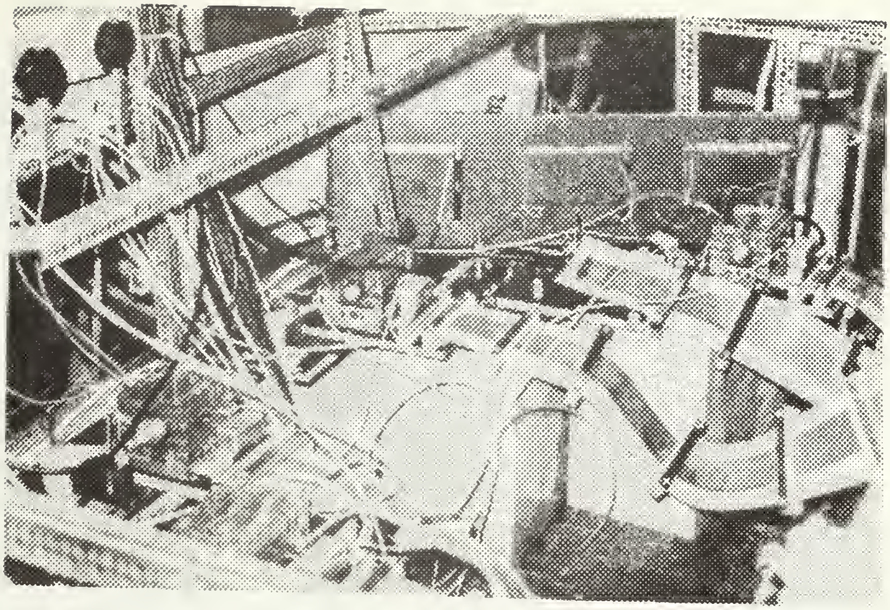

Fig. 16. Capacitor Bank and Spark Gaps for Theta-pinch System.

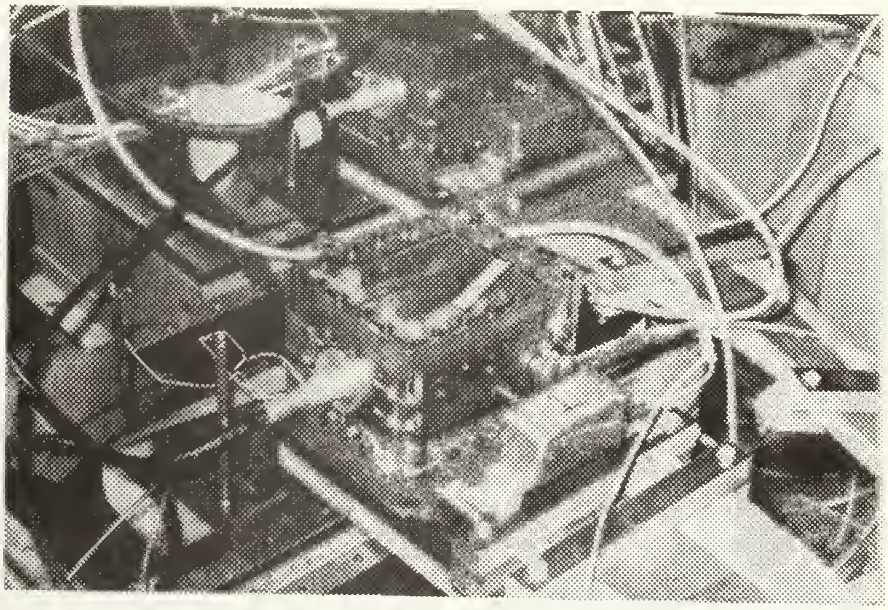

Fig. 17. Spark Gap for Theta-pinch System.

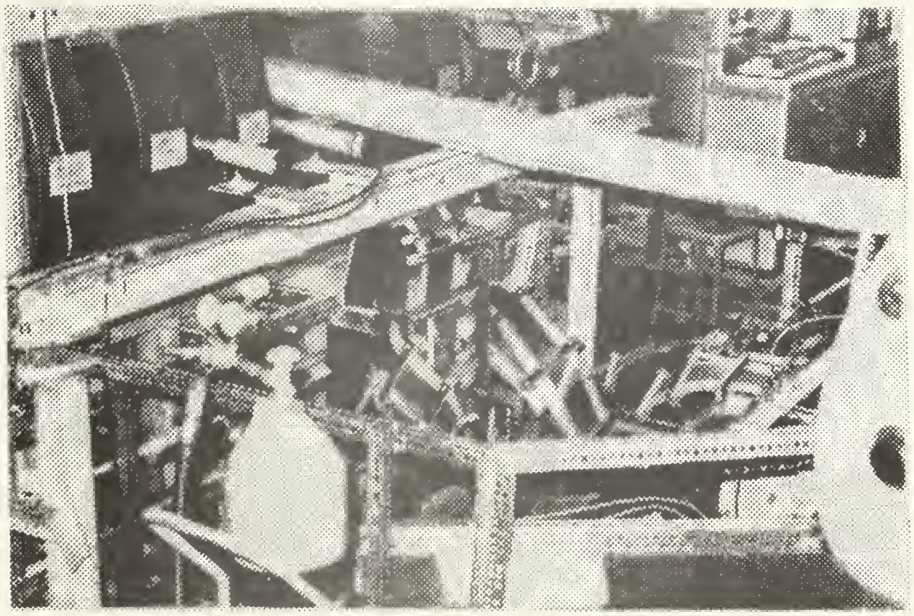

Fig. 18. Strip Line Into Theta-pinch Coil.

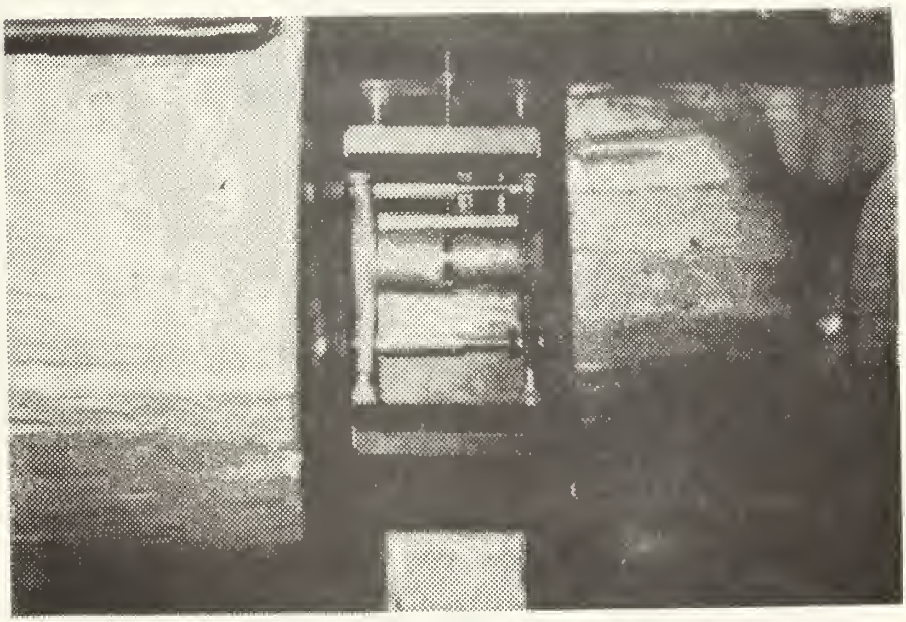

Fig. 19. Theta-pinch Coil.

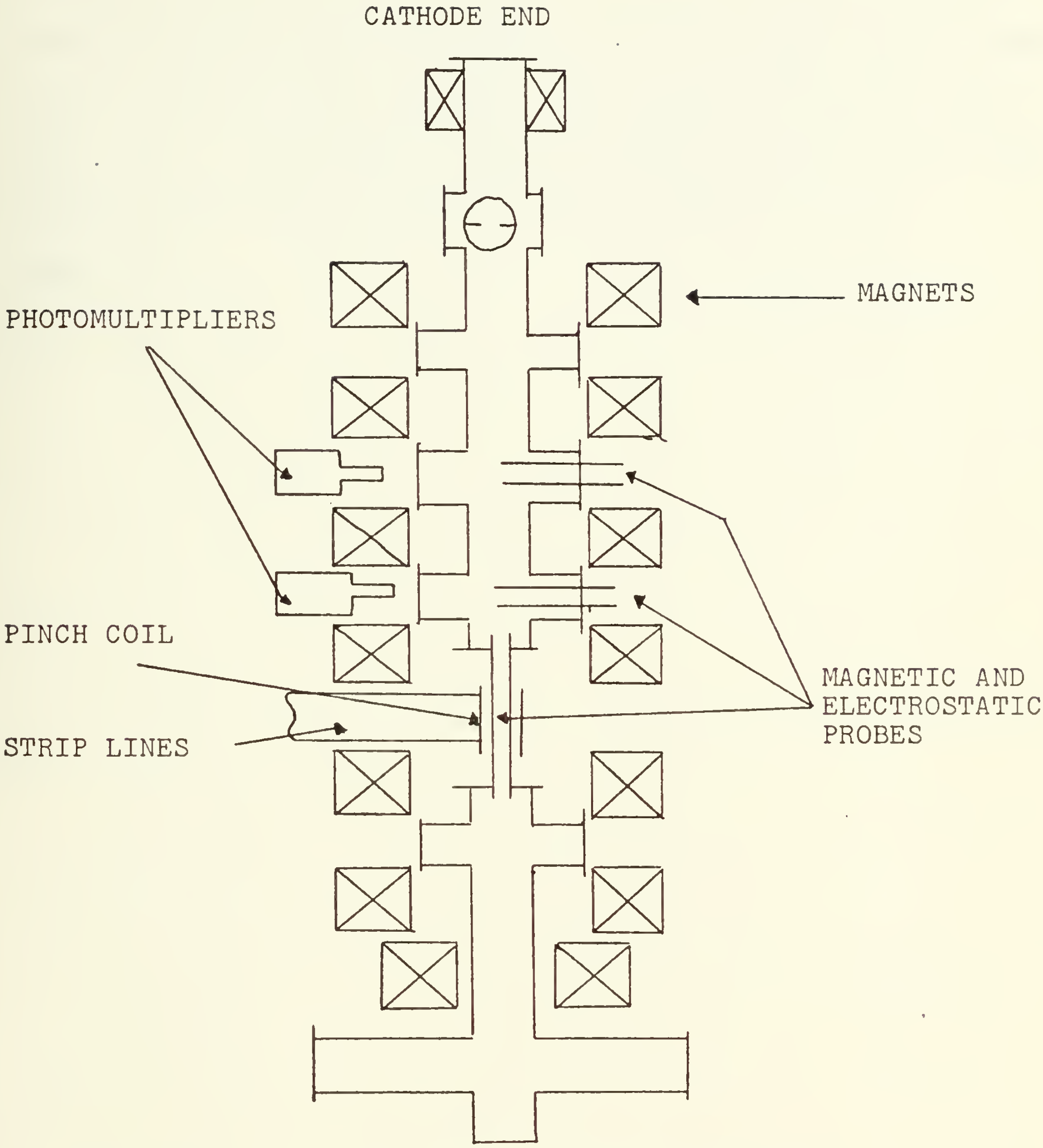

Fig. 20. Plane Top View of Plasma Chamber (From Budzik [12]).

the drift tube. The magnets when on produce an axial magnetic field along the drift tube. The drift tube is 10.16 cm in diameter and necks down abruptly to 5.5 cm to pass through the theta-pinch coil. A parameter of the plasma chamber taken from Christensen [13] is that the maximum confinement induction field is 9600 Gauss. A more complete description of the plasma chamber can be found in Christensen [13] (See Figure 20).

III. OPERATION OF THE SYSTEM

A. THETA-PINCH REDESIGN

The theta-pinch was operated in the configuration which was built by Budzik [12] during the initial part of the experimentation. However during firing of the discharge capacitor bank it was noticed that the capacitors ejected oil and this posed a problem as to the level of the oil in the capacitors and a hazard to the operation of the capacitor bank. The capacitor bank was redesigned to place the capacitors in an upright position (see Figure 16) rather than the horizontal position they were in originally (see Budzik [12]). The spark gap connections to the capacitors were also redesigned. The new system is now set up as in Figure 16. The problem of the oil leakage was corrected.

B. DESTRUCTION OF THE SPARK GAPS BY ARCING

During operation of the theta-pinch in the new design the capacitor bank was charged to 20 KV and arcing between the positive and negative strip lines near the spark gap occurred. The arcing destroyed the spark gap by destroying the plexiglass insulator material between the positive and negative sides of the strip lines (see Figure 21).

This problem occurred twice with two spark gaps destroyed, both occurring during operation at 20 KV. The problem hopefully was solved by making the new spark gaps with 1/8 inch insulator between the strip lines rather than the 1/16 inch

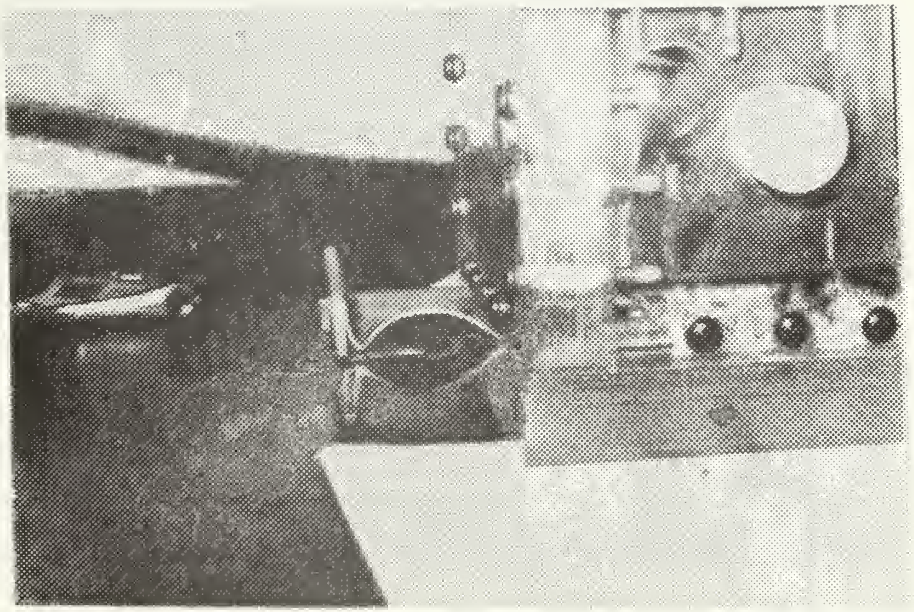

Fig. 21. Spark gap destroyed by arcing. Notice the shattered plastic between strip lines.

previously used. It is recommended that the bank not be charged over 20 KV until all the spark gaps are replaced with the new type.

C. INTEGRATION OF STREAK CAMERA WITH SYSTEM

During experimentation, a streak camera was attached to the system in an effort to take time resolved spectrographic pictures of the shocked plasma as the shock wave propagated past the port (see Figures 22-23). It was hoped that it would be a helpful diagnostic tool. The results of attempts to take a picture were a complete failure to record any light at all even with the mirror stationary. The exposure time of the plasma-produced luminescence is too short to expose the

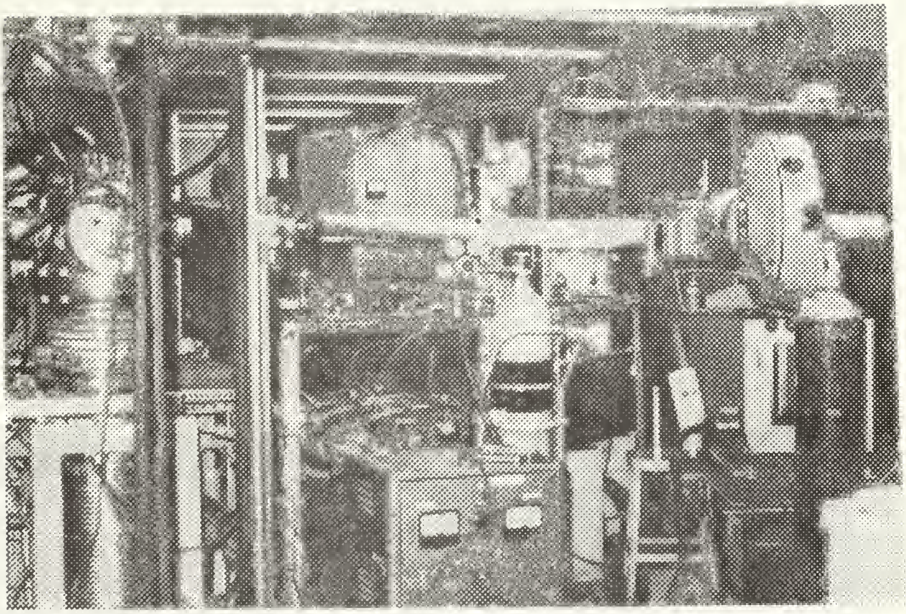

Fig. 22. Streak camera attached to viewing port by tube in effort to take time resolved spectrographic pictures.

in this type of streak camera. Further details of the camera operation and characteristics can be found in Hogan [14].

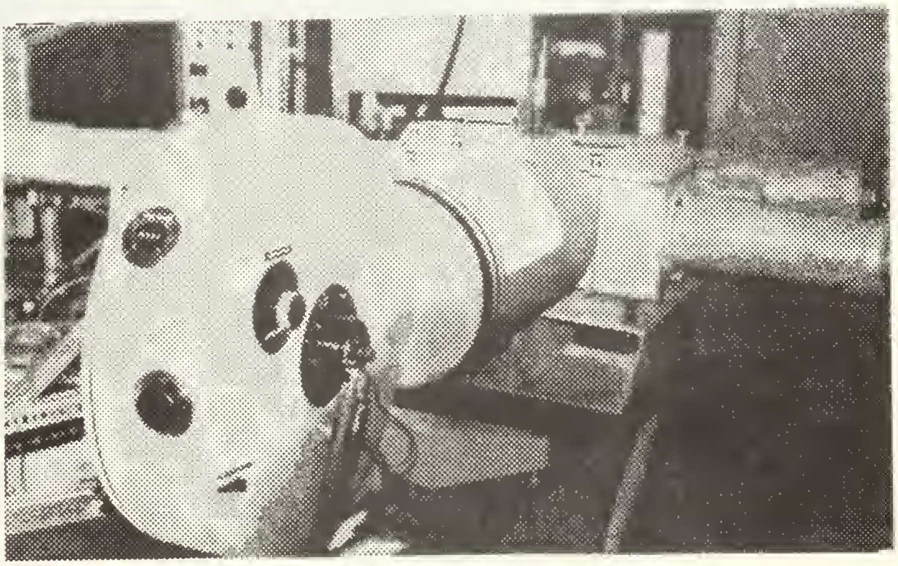

Fig. 23. Streak camera with spectrographic dispersion unit.

IV. RESULTS OF EXPERIMENTATION

A. DIAGNOSTIC EQUIPMENT

Diagnostic equipment used in the experiment were two photomultiplier tubes placed at two viewing ports 28.5 cm. and 63.5 cm. from the center of the theta-pinch coil (see Figures 20, 24) and electrostatic and magnetic probes.

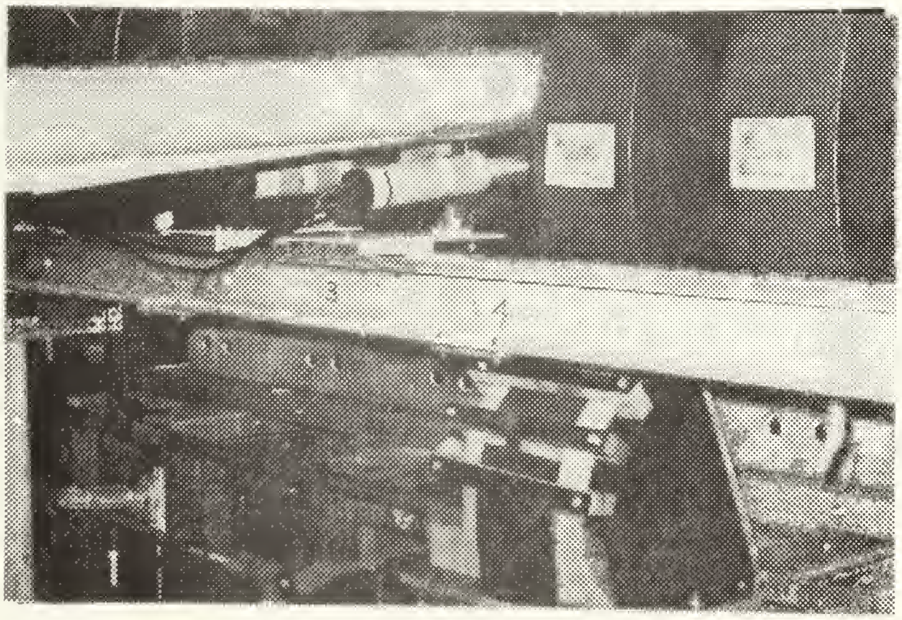

Fig. 24. Photomultipliers in place.

The photomultipliers were used to measure the arrival of the luminous fronts at the respective ports downstream from the pinch to determine the velocity of the shock front. The electrostatic and magnetic probes were used similarly. They were also used in an attempt to detect the precursor electric field predicted by theory and the transverse magnetic field "switched-on" by the shock front. The diagnostic equipment

was fed into an oscilloscope located in an electrostatically shielded cage by coaxial cable and photographic records of the results were made.

B. VELOCITY PROFILES (see Figures 25-27)

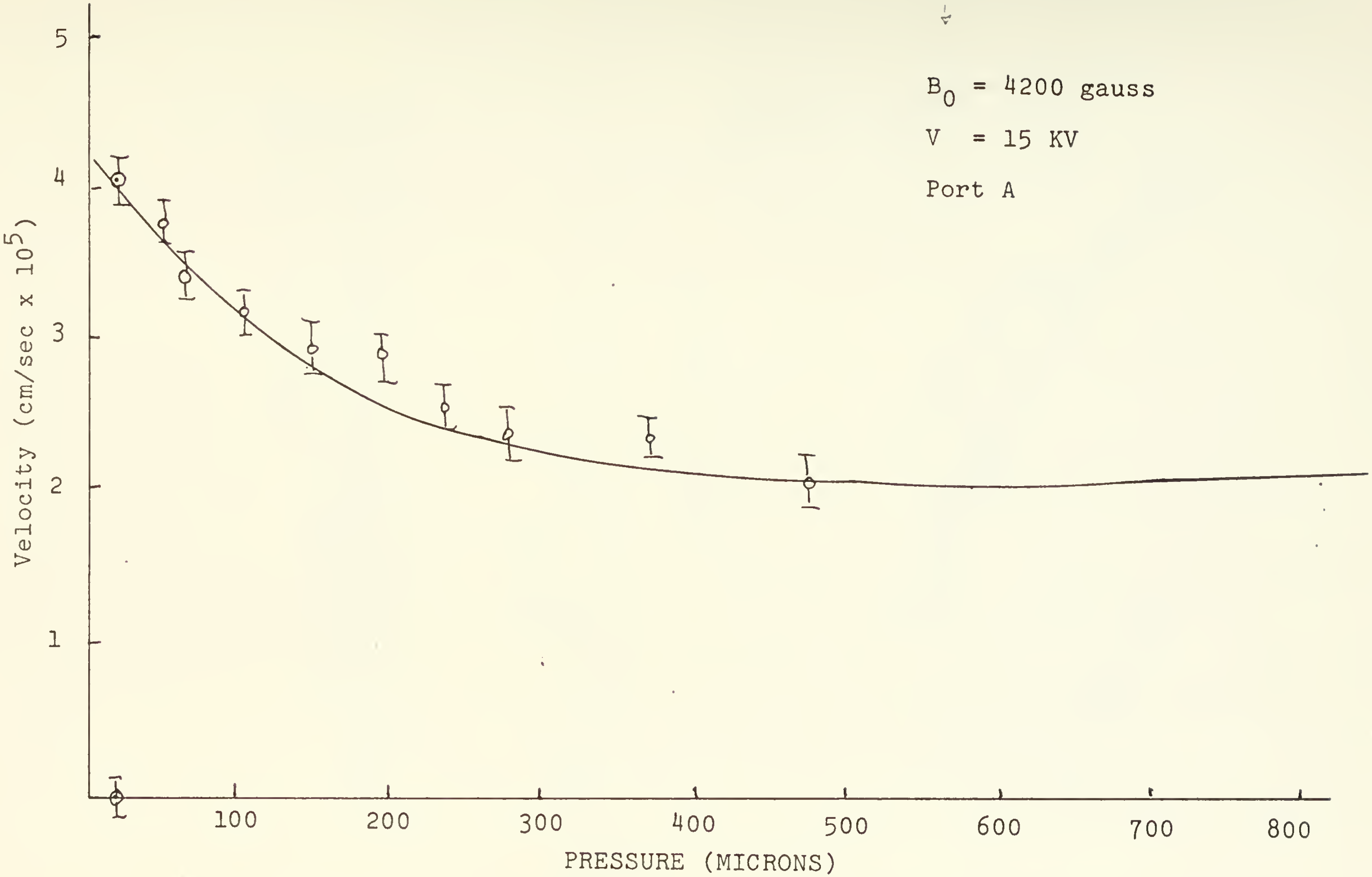

Fig. 25. Velocity of Shock Front vs. Pressure in argon at B_0 = 4200 gauss
Bank Voltage = 15 KV

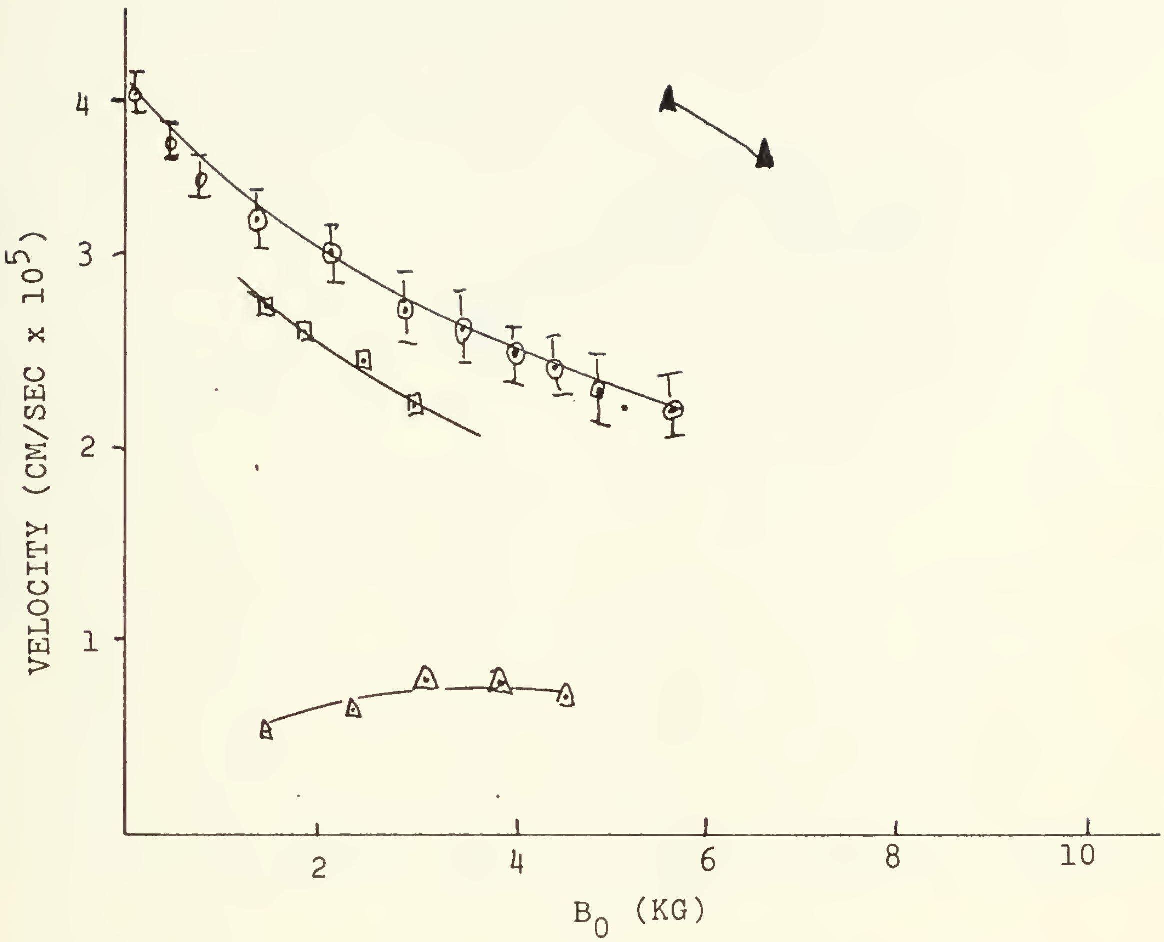

Fig. 26. Velocity vs. applied magnetic field, ⊙- 15 KV Bank Voltage (port A), △- 15 KV Bank Voltage (port B), ☐ - 10 KV Bank Voltage (port A), ▲- 20 KV Bank Voltage (port A); Pressure - 100μ argon.

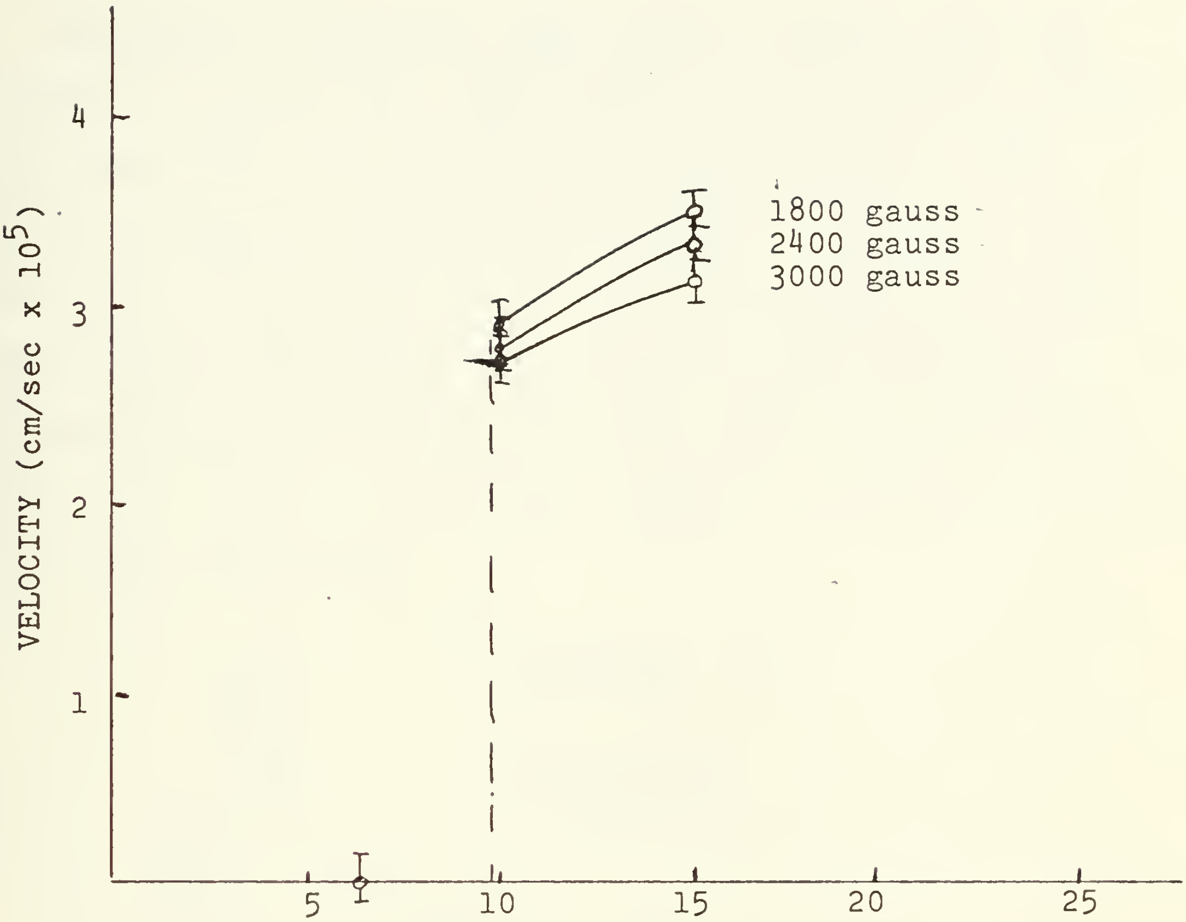

Fig. 27. Velocity vs. Bank voltage for 100 argon for B_0 = 3000, 2400, 1800 gauss. The point for 7 KV is due to equipment limitation. No shock wave was observed below 7 KV.

V. CONCLUSIONS

We compared the graphs drawn and the results with the findings of Levine [3]. The velocity versus pressure profile (see Figure 25), follows that predicted by Levine. The velocities obtained are on the order of one magnitude lower than that of Levine, but this can be accounted for as Levine used hydrogen gas whereas this experiment was conducted in argon. Also Levine made a much wider range of measurements (see Figure 28), in a shock tube compared to these measurements in an open ended pinch.

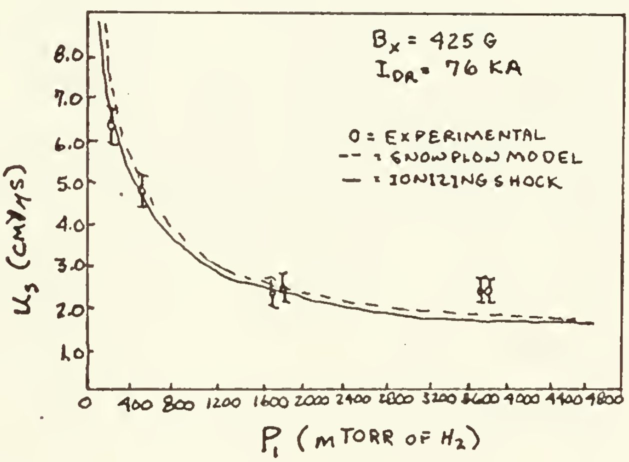

Fig. 28. Shock speed as a function of initial pressure. (Levine [3])

Levine's results for shock speed versus drive current would be analogous to our speed versus bank voltage. However, he has a constant drive current during the operations. In this experiment there is no constant current and the curves

would not necessarily be linear. His results indicate a linear rise along the snowplow theoretical curve. The results of this experiment with a few data points would not be expected to show linearity if any results had been obtained at 7 KV and below. This is probably due to the equipment limitations rather than a cutoff in the velocity profile at 7 KV. The results show definitely that the shock speed increases with increasing bank voltage which was to be expected. In the third graph (see Figure 26), the results show a decrease in shock speed with an increase in the applied magnetic field. This is just the reverse of the results Levine found in hydrogen. Except for port B at 15 KV all the curves show a decline in velocity. It is expected that the velocity would increase. However, this might be a result of the pinch effect being nullified by the trapped field inside the plasma. If the field is large enough the induced field by the pinch will not be strong enough to complete the pinch and the velocity consequently would be lower as the density gradient would also be lower. This is also connected with the cutoff of propagation of the wave and the pinch effect found when over 6000 gauss was applied at a bank voltage of 15 KV and the cutoff of the 10 KV curve at 3800 gauss (see Figure 26). Figures 29 and 30 are the results from Levine [3].

This experiment created velocities of the shock wave which were very sub-Alfvenic. The sound Mach numbers were on the order of Mach 12 to 16. M_A was equal to 0.56.

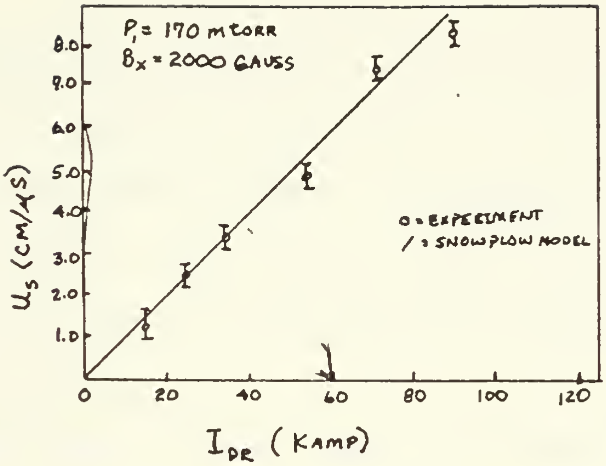

Fig. 29. Shock speed as a function of drive current. (Levine [3])

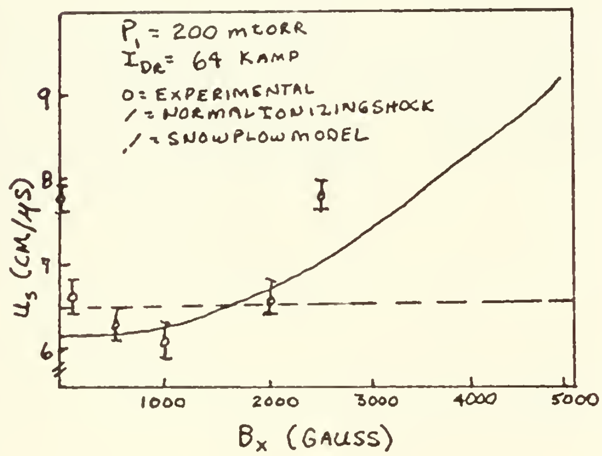

Fig. 30. Shock speed as a function of applied longitudinal magnetic field. (Levine [3])

VI. RECOMMENDATIONS FOR FURTHER STUDY

Recommendations presented here are for system improvements.

1. The spark gaps should all be replaced with the eighth inch plexiglass sheets versus the sixteenth inch sheets and this may allow the bank to be charged to the full 25 KV maximum not attainable in this project due to the strip arcing previously mentioned.

2. The plasma column should be reduced in total to the diameter of the pinch coil to reduce losses and turbulence caused by the expanding plasma transitioning from a small diameter to a large diameter abruptly. This could be achieved by placing a sleeve inside the existing chamber.

3. The theta-pinch should be improved to decrease the rise time of the current to the nano-second range versus the microsecond range now available. This would require a Blumlein type transmission line.

APPENDIX A

THETA PINCH OPERATING PROCEDURES

I. Evacuating Plasma Chamber

   A. Preliminary checks

   B. Evacuation of Foreline and booster manifold

   C. Starting of Diffusion pumps and refrigerator (only for pressure below 50 microns)

   D. Initial Evacuation of Plasma chamber with Mechanical Forepump (Rough Pumping)

   E. Final evacuation with Diffusion Pumps

   F. Introduction of Desired Gas Mixture

   G. Overnight standby

   H. Returning system to Atmospheric Pressure

II. Magnetic Field Operation

   A. Preliminary steps

   B. Main magnets

   C. Mirror Magnets

III. Theta Pinch Operations

   A. Pressurizing of Spark Gaps

   B. 50 KV Power Supplies

   C. Monitoring System

   D. Charging of System and Firing

   E. Shut down of system

SECTION I: Evacuation of Plasma Chamber

A. Preliminary Checks

At South End of Machine: (Figure 30)

1. Check that manual throttle valve is closed

2. Check that water pressure gauge reads 40psi

3. Check the air pressure regulator gauges read 80 - 100 psi

4. Check that the vents are closed

At North End of Machine:

5. Check that ambient water valve is wide open

6. Check DP inlet and outlet cooling valves are reopened if they have been closed for repairs (normally open)

7. Check that the toggle gate valve is open. If closed, crack it open slightly, wait for pressure to equalize and open fully.

At West Side of Machine:

8. Check that DP water cooling valves are open.

At Cooling Pad (outside)

9. Check that the forepump cooling water discharges in a slow steady stream. Adjust as necessary. (Water valve has loop of wire in its handle)

At Console (right-hand side...Figure 31)

10. Switch Control power CKT 25 ON

11. Close Air Interlock relay by pressing Air button. (Figure 1)

12. Close Water Interlocking relay by pressing Water button. (Figure 1)

13. Set Mode selector switch to Start Forepump (Figure 1)

14. Set Forepump meter-relay red pointer to 30 microns.

15. Set booster meter-relay red pointer to 1000 microns. (Figure 32)

16. Check to see that gate valves V_1-V_6 and V_{10} are closed. If not, close. (Figure 31)

17. Observe whether the Booster Manifold gate valve, V_7, is open or closed. If it is closed, do not open until the pressure is the same on both sides of the valve. This condition may be satisfied by venting both the booster manifold and forepump lines to atmospheric pressure and close vent valve and open V_7.

B. Evacuation of the Foreline and Booster Manifold

1. Start forepump by pressing forepump Start button (at the wall, Figure 2). Pressure should drop to 100 microns in two minutes.

2. When pressure reaches 50 microns, move the red meter-relay pointer to meet the meter needle.

3. Set the booster meter relay to 100 microns.

C. Evacuation of Chamber (Below 50 microns)

1. Press Forepressure button on interlock chain. Light should come on.

2. Set mode selector switch to <u>Run</u> <u>Forepump</u>.

3. Move mode selector switch to <u>Start</u> <u>DPS</u>, <u>REFRIG</u>, (Red light should come on)

4. Switch DP's, Including 10" DP, to ON if not already on: Record time in Vacuum Log Book.

5. Switch Refrigerator to <u>ON</u>. Listen for violent convulsive noise indicating an overload. If heard switch <u>OFF</u>, and wait one minute and try again. If heard again conduct maintenance.

6. Allow 20 minutes for warm-up. Part D can be performed while waiting.

D. Initial Evacuation of Plasma Chamber with Mechanical Forepump. (Rough Pumping)

1. Observe Thermocouple gauges T_2-T_4, to determine pressure of chamber. (Figure 32)

a. If the pressure is less than 50 microns go to part E, if desired.

b. If the pressure is between 50 - 200 microns, go to step 2g.

c. If the pressure is 200 - 1000 microns, go to 2b.

d. If the pressure is greater than 1000 microns go to step 2a.

2. a. Close hand throttle valve.

b. Set Booster-relay meter to 200 microns.

c. Open valve number 6 (V_6) between plasma chambers and foreline. If booster manifold pressure approaches 100 microns close V_6 and open V_7 until pressure is below 20 microns.

d. Gradually open throttle valve. Note smoke from forepump vent pipe and adjust throttle to avoid an excessive amount.

e. Observe manometer gauge. If indicator needle hasn't moved, check that the cathode valve is open. If the manometer still reads a pressure higher than 29 inches of mercury after one minute, a gross leak is indicated.

f. Observe the thermocouple gauges T_2-T_4. When the pressure drops below 20 microns you are ready to continue to lower pressures or add gas for experimentaticn.

g. Fill foreline trap with liquid nitrogen (LN).

h. When pumping down below 50 microns close V_6. Rough pumping is completed and proceed to part E.

E. Final Evacuation with Diffusion Pumps

1. Press and release baffle interlock button. Signal light should remain on.

2. Prepare ionization guage to read pressure

a. Check that power switch is on for both the ionization gauge and the Ion Gauge Standby.

b. Set the pressure multiplier to 10^{-4}.

c. Turn both Ion Gauge Standby selector switches to a desired position.

d. Check that Outgassing switches are OFF.

3. Open V_{10}, then V_1-V_5 and record time in the vacuum log. The chamber pressure should drop to one micron.

4. Switch ion gauge on by simultaneously pressing:

   a. Filament on (ionization gauge)

   b. Reset (ion gauge standby)

   A pressure of less than 10×10^{-4} torr (mm Hg) should be obtained. If the needle goes off the scale and switches off, the pressure is greater than 15×10^{-4}. Wait one minute and try again. If still offscale, see lab technician for advice.

5. If reading is on scale, set zero by switching filament off at ion gauge standby and adjusting zero control. Then turn filament on again.

6. Read grid current by raising READ CURRENT toggle. (Should read about 1.0 ma)

7. If the pressure reads below 1.0×10^{-4} torr, the Pressure Multiplier may be set to lower multiples. Recheck zero and grid current and adjust as necessary.

8. Set the booster meter relay at 80 microns. A pressure rise about this amount will trip the interlock safety circuit, closing the valves, and cutting off the DP's and refrigeration. A failure of power, water pressure, or air pressure will do likewise.

9. To operate vacuum pumps unattended, the mode selector switch may be set at RUN DPS. At this setting the chamber is protected against a rise in either pressure or baffle temperature.

10. Check that the cooling water outlets from the DPS are lukewarm. Adjust water flow as necessary.

11. Continue pumpdown until desired background pressure is reached.

F. Introduction of Gas for Experiment

1. Open valve on tank or tanks of gas to be used.

2. Adjust manifold valves to gasses to be used to get desired mixture. (Figure 32)

3. Open micrometer valve to admit the gas to the chamber and observe the pressure on thermocouples or ionization gauges to attain desired amount.

G. Overnight Standby

1. Close metering and bypass valves if open.

2. Close gate valves V_1-V_5 and V_{10} if open.

3. Shut off refrigerator if on.

4. If DP's are on, leave them on until leaving for the day. Then turn them off.

5. Set Mode Selector switch at Run Forepump.

6. Set booster meter relay pointer at 100 microns.

H. Returning to Atmospheric Pressure

1. Close gate valves V_1-V_6 and V_{10} if open.

2. Close gas metering valve if open.

3. Close all gas manifold valves

4. Open nitrogen cylinder valve to about 10psig.

5. Open nitrogen manifold valve.

6. Carefully open bypass valve to admit nitrogen to the chamber.

7. Observe thermocouple gauges to check initial pressure rise in the chamber. If no change is observed check to see that cathode valve is open.

8. Observe gas feed manometer while nitrogen is flowing into the chamber. As pressure approaches atmospheric, close bypass valve.

9. When the static pressure reads atmospheric, close the bypass valve and the gas manifold valve.

10. Close cylinder valve.

11. Shut Off Forepump.

12. Vent Foreline

13. Turn off Water.

Section II: Magnetic Field Operations

A. Preliminary Steps

1. Fill pure water line.

    a. Close de-ion loop valve (at cooling tower).

    b. Open main water 3/4 to 1 turn.

    c. When expansion tank is 2/3 full start the Pure Water Circulating pump and the Raw Water Circulating pump.

    d. Observe the overflow outlet outside. When water emerges close the main valve and open the de-ion loop valve.

2. Turn off Ion Gauge #4 (at console).

3. Check that no magnetic material has been left near the machine.

4. Warn personnel to remove watches to a safe distance (20 feet).

5. Connect blower at reflex anode.

6. Start Cooling tower check to insure its operation.

7. Observe water flow in all meters and check hoses for leaks.

8. Turn ON Control Power CKT 21, Push three interlock buttons. (Figure 33)

9. For Main Magnets, set Control Power CKT 19 to ON. If it kicks out, reset circuit breaker, then restart and set Standby switch ON. The standby condition is confirmed by the roar of the rectifier fans.

10. Consult magnetic chart page 58 for operating conditions to give desired field; switch ON approximate number rectifiers at the console.

B. Main Magnets

1. To start the main magnets (red coils), press ON button under the MAIN Magnet.

2. Adjust rheostat to give desired current for Field (100 amps = 600 gauss).

3. Record time and current in Magnetic log.

4. Do not run unless needed, the magnets can be turned OFF and ON as needed.

5. To Stop, press OFF button and Log the time in the Magnetic log.

C. Mirror Magnet

1. Turn Mirror magnet rectifier power switch ON. (It is located in shed nearest door.)

2. To start, press ON button under Mirror.

3. Adjust dial to give desired current.

4. Record time and current in Magnet Log.

5. To stop, press OFF button.

Section III: Theta Pinch Operations

A. Pressurizing of Spark Gaps

1. Open cylinder valves on the master and slave nitrogen tanks.

2. Set the regulator valves to desired pressures on the slave and master gaps. (Master 35psig and slaves 1 psig per KV charging voltage. 15 KV charge = 15 psig.)

3. Check pressure gauges at capacitor bank to insure pressure is correct.

4. Remove C clamps from capacitor bank.

B. 50 KV Power Supplies (Figure 34)

1. Turn on circuit breaker #10.

2. Press system start button on large power supply.

3. Turn top row of interlock switches on. (There will be a two minute wait for High Voltage relay to come on.)

4. Go to small power supply and turn on all breakers at lower left hand corner.

5. Press VOLTAGE ON button.

6. Go to Trigger system cabinet and turn High Voltage switch ON (one minute delay)

7. Set High Voltage at 12.5 KV.

8. Set current dial at 17 - 18 ma.

9. On large power supply press VOLTAGE ON button and regulate to 35KV.

C. Monitoring System

1. Turn on power supply at capacitor bank to 30 volts and turn switch on light panel ON (all lights should light.)

2. Push reset button to reset lights (lights on indicate firing of spark gap).

D. Charging of System and Firing

1. Purge slave and master gaps at firing panel.

2. Press master charge button (charged light should come on).

3. Set regulator on 50 KV cage to desired bank voltage (0-25KV)

4. Press charge button for slave bank (red light on capacitor bank should blink and door chimes ring).

5. Turn small 50 KV supply rheostat to the 50 KV position.

6. When charged the capacitor bank will cause a siren sound.

7. Push Fire button when ready.

8. Turn small 50 KV supply rheostat to zero.

E. System Shut Down

1. At the small power supply turn OFF circuit breakers at lower left (4).

2. Press High Voltage Off button on large power supply and turn rheostat down to zero.

3. Press system Off button on large power supply.

4. Turn High Voltage circuit breaker at bottom of large power supply OFF.

5. Throw circuit breaker #10 at panel OFF.

6. Turn OFF all rheostats on Firing panel to zero.

7. Turn OFF High Voltage and current toggle switches.

8. Close valves to nitrogen cylinder on Slave and Master Spark gaps.

9. Purge Slave and Master gaps to normal atmosphere.

10. Turn High Voltage toggle switch Off at firing panel.

11. Use grounding stick to insure all capacitors are grounded and discharged, then replace C - clamps.

12. Turn OFF monitor circuit power supply if on.

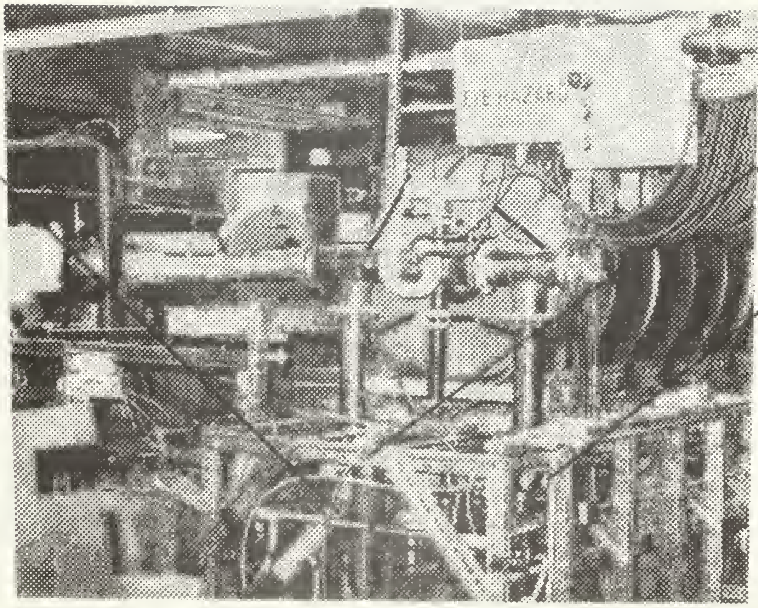

Fig. 31. Plasma Machine - South End

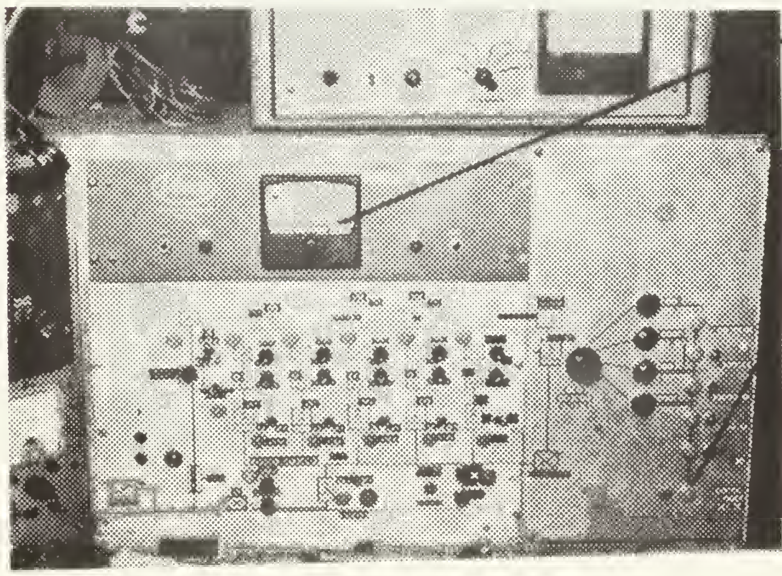

Fig. 32. Vacuum Control Panel

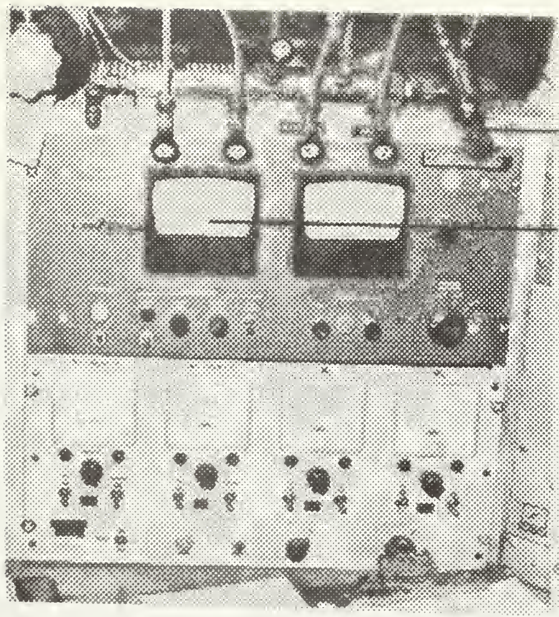

Fig. 33. Pressure Gauges and Gas Manifold

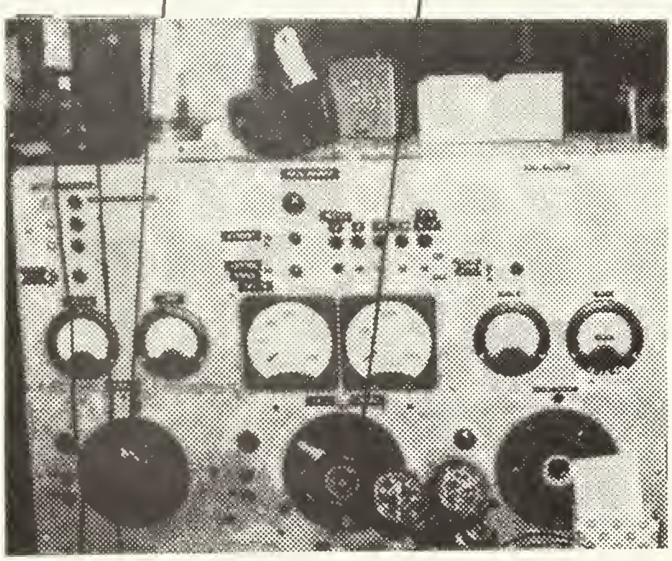

Fig. 34. Magnet Control Panel

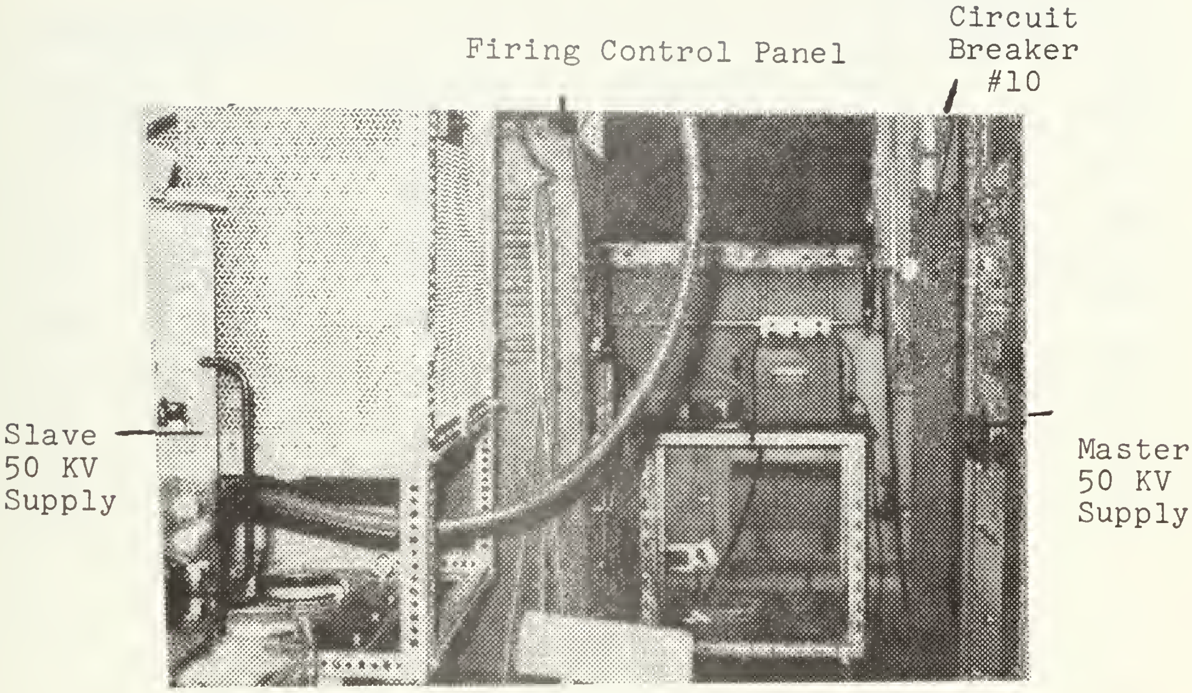

Fig. 35. Theta-Pinch Power Supplies

RANGES OF MAGNETIC FIELD INTENSITY

MAGNET CURRENT (amperes)			MAGNETIC FIELD INTENSITY (gauss)	
Rectifiers connected	Min curr.	Max curr.	Min	Max
No. 2 (master)	100	230	600	1380
Nos. 2 and 3	190	470	1140	2820
Nos. 2,3 and 4	280	750	1680	4500
Nos. 2,3,4, and 5	320	820	1920	4920
Nos. 2,3,4,5 & 6	450	1075	2700	6450
Nos. 2,3,4,5,6,7, 8,9, & 10	660	1600	3960	9600

(100 amperes = 600 gauss)

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13. ABSTRACT

A study was made of shock waves produced in neutral argon gas by a theta-pinch device. From the study, graphs were made of the velocity of the shock wave observed versus the applied magnetic field, the bank voltage of the capacitor bank, and the argon pressure in the plasma chamber. The velocity of the shock front varied with the parameters as follows:

Parameter Varied	Range	Velocity
Pressure	20 microns	4.01×10^5 cm/sec
	1000 microns	2.20×10^5 cm/sec
Applied Magnetic Field (for 15KV)	0 Gauss	4.00×10^5 cm/sec
	6000 Gauss	2.10×10^5 cm/sec
Applied Magnetic Field (for 10KV)	1800 Gauss	2.6×10^5 cm/sec
	3600 Gauss	2.3×10^5 cm/sec
Bank Voltage	15 KV	3.25×10^5 cm/sec
	10 KV	2.50×10^5 cm/sec

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
theta-pinch						
shock waves						
argon						
precursor						
alvenic mach number						
spark gap						

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